REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 01/17/2014	**2. REPORT TYPE** Interim Research Performance Report (Monthly)	**3. DATES COVERED** *(From - To)* December 1 - December 31, 2013

4. TITLE AND SUBTITLE Expeditionary Light Armor Seeding Development	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER N00014-13-1-0219
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Nichole Cicchetti, Bazle Haque, Shridhar Yarlagadda	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) UNIVERSITY OF DELAWARE OFFICE OF THE VICE PROVOST FOR RESEARCH 220 HULLIHEN HALL NEWARK, DE 19716-0099	**8. PERFORMING ORGANIZATION REPORT NUMBER** MONTHLY-9
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 875 North Randolph Street Arlington, VA 22203-1995	**10. SPONSOR/MONITOR'S ACRONYM(S)** ONR
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for Public Release; distribution is Unlimited.

20150928134

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The University of Delaware Center for Composite Materials (UD-CCM) is developing the next generation of lightweight hybrid ceramic/composite armor kits for Marine Corps tactical and combat vehicles. The focus will be on simulating and modeling the performance of ceramic/composite lightweight armor at seams and corners, and improving the armor's performance in these regions. The light ceramic/composite armor is comprised of composite backings, adhesives, ceramics and covers. This is an expansion of previous research on performance-weight-cost evaluations and center strike experiments and simulations done on these materials.
The effort of this modeling and simulation are to down select for appropriate geometries to improve the performance of seams and corners. The tiles will be restricted to the sintered ceramics (SiC) due to the ability to fabricate SiC into complex geometries. Model ballistic experiments will validate the modeling done in simulation.

15. SUBJECT TERMS

.30cal AP M2 Projectile, 762x39 PS Projectile, SPH, Aluminum 5083, SiC, DoP Expeminets, AutoDyn Simulations, Tile Gap

16. SECURITY CLASSIFICATION OF: UU			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Shridhar Yarlagadda
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	UU	10	**19b. TELEPHONE NUMBER** *(include area code)* 302-831-4941

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Modeling and Simulation of Ceramic Arrays to Improve Ballistic Performance

Nicole A. Cicchetti, Bazle Z. (Gama) Haque, and Shridhar Yarlagadda
University of Delaware Center for Composite Materials (UD-CCM)
Newark, DE 19717; E-mail ncicc@udel.edu

Abstract

The University of Delaware Center for Composite Materials (UD-CCM) is developing the next generation of lightweight hybrid ceramic/composite armor kits for Marine Corps tactical and combat vehicles. The focus will be on simulating and modeling the performance of ceramic/composite lightweight armor at seams and corners, and improving the armor's performance in these regions. The light ceramic/composite armor is comprised of composite backings, adhesives, ceramics and covers. This is an expansion of previous research on performance-weight-cost evaluations and center strike experiments and simulations done on these materials.

The effort of this modeling and simulation are to down select for appropriate geometries to improve the performance of seams and corners. The tiles will be restricted to the sintered ceramics (SiC) due to the ability to fabricate SiC into complex geometries. Model ballistic experiments will validate the modeling done in simulation.

Objectives and Goals

The goal of this study is to generate computational models of ceramic behavior based on various geometries of seams and corners. The models of the geometries of interest will be used to down select for the optimal geometries of seams and corners that provide improved performance over the baseline measurements of wave propagation, fracture, and damage at seams and corners. The proposed effort will be modeling accurately model ceramic behavior in a computational setting and improve the performance of the seams and corners of ceramic tile faced armor.

Methodology

Using a modeling and simulation, many seam geometries can be qualitatively tested with accurate predictions. The modeling and simulation approach provides an accurate prediction of the performance of ceramic array configurations, allowing down selection for the most effective seam configurations.

1. Establish a baseline of materials properties and projectile characteristics for modeling.
    a. Models are developed in AUTODYN and relatively small/coarse (<1M degrees of freedom).
    b. Baseline ceramic tiles – Sintered SiC

    c. Baseline backing – Al5083 for initial studies, S-Glass/Phenolic for further study

2. Identify models of improved seam and corner performance of ceramic tile arrays.
    a. Key modeling parameters are tile gaps, local tile thickness, filler materials, additional materials under or over the seams and corners and tile overlap.
3. Down Select concepts that show improved performance, validate with single tile model experiments.
4. Model selected concepts with composite backing, and qualitatively predict performance compared to baseline selection of concepts for experimental evaluation.
    a. Model development in LS-DYNA, with MAT162 composite damage model.

Modeling and simulation of ceramic composite systems will be performed using explicit dynamic hydrocode LS-DYNA and AUTODYN. Computational models with less than one million (1M) degrees of freedom will be solved using AUTODYN and models with greater than five million (5M) degrees of freedom will be solve using LS-DYNA.

AUTODYN and LS-DYNA provide databases of material properties, which include fundamental Equations of State, Strength Models, Failure Models, and Erosion Models. Materials from the database will be used when modeling the projectile and the armor. The typical material models that are used and that are being used in these computational models are presented in Table 1.

Table 1: Material Models

MATERIAL	EOS	STRENGTH MODEL	FAILURE MODEL
Steel Core	Polynomial	Johnson & Cook	Johnson & Cook
Lead Filler	Gruneisen	Piecewise Johnson & Cook	N/A
Copper Jacket	Linear	Piecewise Johnson & Cook	N/A
SiC Ceramic	Polynomial	JH-2	JH-2
Aluminum	Polynomial	Johnson & Cook	Johnson & Cook
S-Glass/Phenolic	Linear	LS-DYNA MAT162	LS-DYNA MAT162
Polymeric Foam	Linear	Non-linear Elastic	N/A
Adhesives & Interlayers	N/A	Cohesive Laws	Cohesive Laws

Aluminum will be used as the ceramic backing as the stiffness and wave speed is equivalent to S-Glass/Phenolic composites. The simulations address shockwave propagation, ceramic fracture and damage mechanics of the geometries of interest.

The overall methodology is to:

- Model ceramic geometries at seams and corners with Aluminum as the backing material, as aluminum has similar properties to S-Glass/Phenolic.
- Down select promising configurations based on the computational models of wave propagation, fracture and damage compared to baseline configuration.
- Model experiments to validate model predictions for selected configurations.
- Model ceramic/composite/cover with selected configurations – selected tile as well as arrays and preform qualitative assessment of performance compared to baseline.
- Fabricate optimal solutions based on model predictions for test and evaluation.

Results and Discussion

Baseline Solution Description

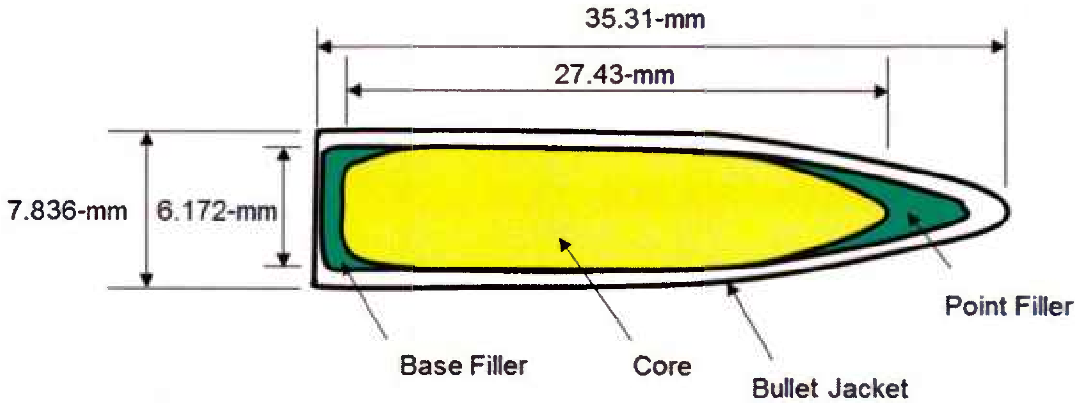
The baseline composite armor configuration is a composite backing, in simulation using aluminum, SiC ceramic tiles and then a composite cover. These layers are bonded together with a high elongation adhesive. This arrangement is chosen for lightweight and ability to manufacture complex geometries for SiC ceramic tiles. The baseline projectiles of interest are 0.30 caliber APM2 round with a steel penetrator and a 0.50 caliber Fragment Simulating Projectile (FSP).

Concept Tile Concepts for Seams and Triple Points

Discreet square, rectangular, and hexagonal ceramic tiles used in ceramic armor systems have gaps between adjacent tiles in the form of seams and triple points. These areas lack the volumetric confinement and produce complex shock patterns, damage and permanent failure when impacted by a projectile. This ultimately yields lower ceramic performance at seams and triple points than when a tile is struck in the center.

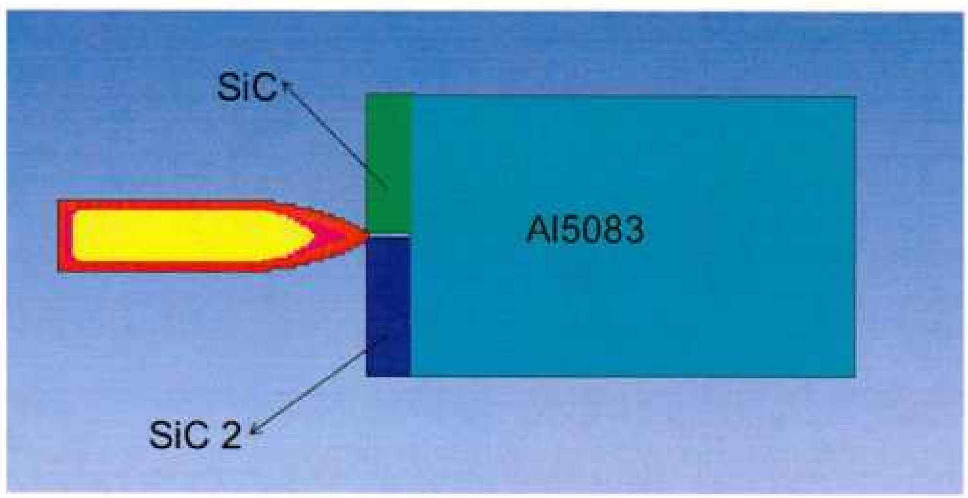
The proposed solutions are as follows (i) increasing the thickness of the outer edges of the tiles, (ii) providing stiffer supports at the ceramic boundaries, and (iii) inclined and/or overlapping ceramic tile edges. These concepts are simulated using computational modeling in AUTODYN and LS-DYNA. These simulations will be compared to baseline testing on tile gaps to quantify the improvement in performance. Solutions that show an improvement will be down selected for fabrication and ballistic testing; this will also serve as the model validating experiments.

.30 Caliber APM2 Projectile Dimensions

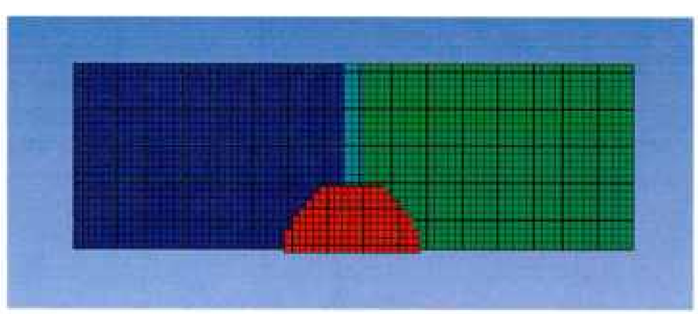


Half Symmetric Model of Projectile and Tile with Gap Modeled in AutoDyn (a) Side View (b) Front View

(a)



(b)



Smoothed-particle hydrodynamics (SPH) is applied for all parts. The SPH particle size is .4 mm, with the assumption that modeling dust smaller than .4 mm can be ignored. A stationary boundary is applied on the edges. The two tiles SiC and SiC 2 are identical with the same dimensions and properties. They are utilized as different materials to differentiate the damage on each tile. The gap size will be changed for different simulations.

Results

DOP is calculated as

$$DOP = L - L_{NP}$$

Where L is the length of the entire target, SiC tiles and AL5083 backing, and L_{NP} is the length of the target left unpenetrated when the velocity and kinetic energy of the projectile have reached zero. This is measured from where the ceramic tile has been embedded into the aluminum.

The DOP will be used to analyze the performance of the seams by comparing the DOPs to the DOPs on one tile tests.

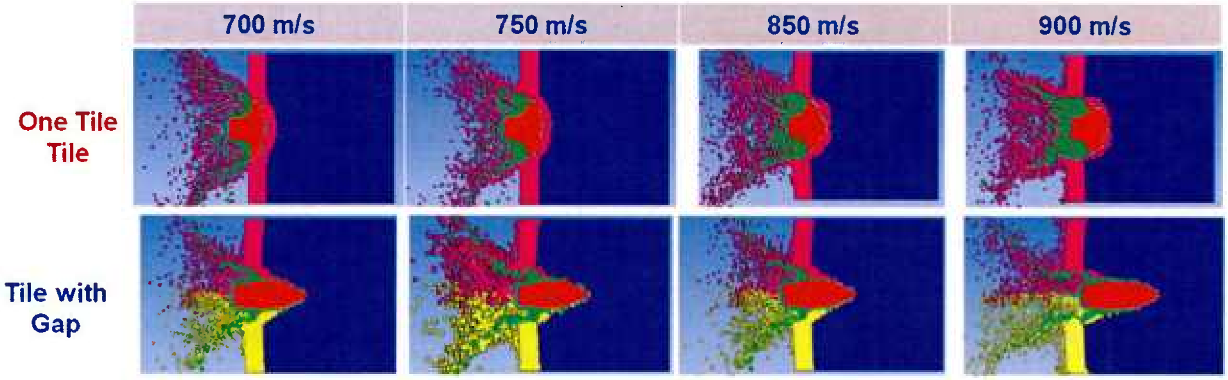
The first computational models run were to compare experimental tests done on one tile to the computational model of one tile. Using the same parameters, the tile with a gap is modeled. The absolute error value between the experimental data and the computational data was found to be 8.56 mm, and considered acceptable.

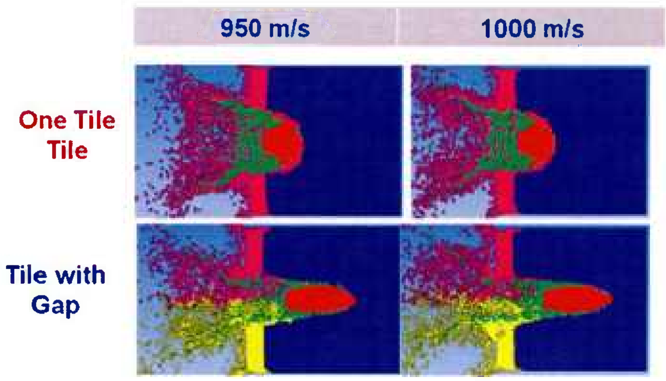
Computational models were run on one tile and tiles with gaps for varying projectile velocities to compare the performance of each arrangement. Results are presented in the following table.

Table 2: Effect of Tile Gap on DOP at Varying Velocities, Gap Size is 1.2 mm

Velocity (m/s)	One Tile DOP (mm)	Tile w/ Gap DOP (mm)
700	10.02	16.40
750	8.59	18.70
850	10.00	24.05
900	11.13	20.04
950	12.96	28.00
1000	14.31	30.28

DOP of One Tile and Tile with Gap at Varying Velocities



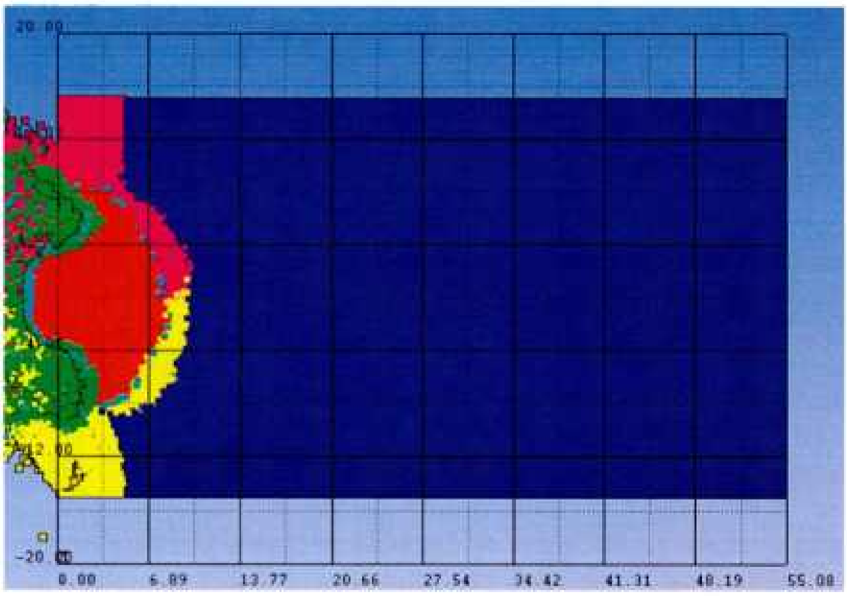


Computational models were then run on models with gap sizes 0.508 mm and 1.061 mm, with projectile velocity at 850 m/s. Thickness was added to the tiles ranging from 1 mm thicker to 4 mm thicker to determine the point where the performance of the gap would be equivalent to the performance of one tile.

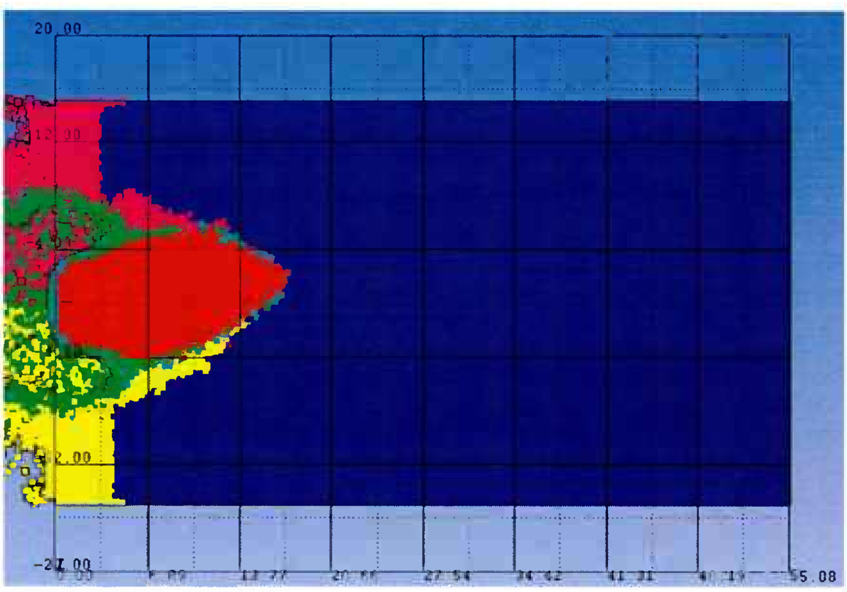
Table 3: Depth of Penetration on Baseline Tiles and Modified Tiles at 850 m/s, Gap Size 0.508 mm		
Gap Size (mm)	**Tile Modification**	**Depth of Penetration (mm)**
None (0)	Baseline	10.33
0.508	Baseline (0 mm extra)	17.19
0.508	1 mm Thicker	14.00
0.508	2 mm Thicker	11.40
0.508	3 mm Thicker	10.80
0.508	4 mm Thicker	9.83

At a gap size of 0.508 mm adding 3 mm of extra thickness to the 5.08 mm thick tile results in in a DOP that is near the baseline result of DOP for no gap.

Depth of Penetration with No Gap



Depth of Penetration with a Gap Size 0.508 Baseline (No Modifications)



Depth of Penetration with a Gap Size 0.508 3mm of Increased Thickness

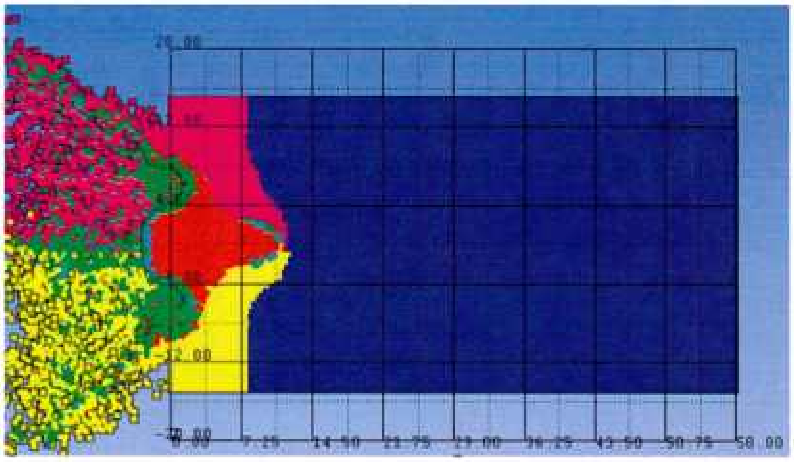
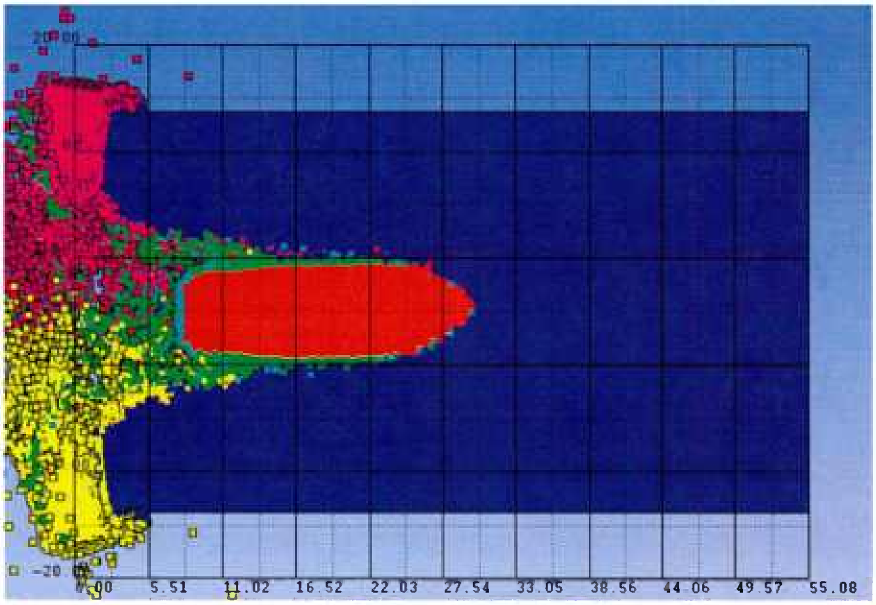


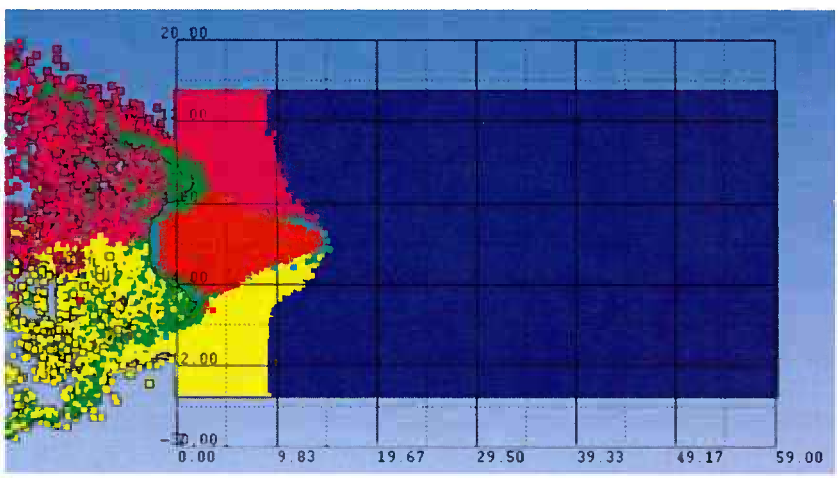
Table 4: Depth of Penetration on Baseline Tiles and Modified Tiles at 850 m/s, Gap Size 1.061 mm		
Gap Size (mm)	**Tile Modification**	**Depth of Penetration (mm)**
None (0)	Baseline	10.33
1.061	Baseline	30.29
1.061	1 mm Thicker	20.95
1.061	2 mm Thicker	16.76
1.061	3 mm Thicker	16.59
1.061	4 mm Thicker	14.77

At a gap size of 1.061 mm almost doubling the thickness of the tile still does not achieve the baseline DOP of tiles with no gap. A better seam solution must be found if a gap size of 1.061 is the best that can be achieved on a manufacturing level.

Depth of Penetration with a Gap Size 1.061 Baseline (No Modifications)



Depth of Penetration with a Gap Size 1.061 with 4 mm Increased Thickness



Discussion

Increased tile thickness is one solution for increasing seam performance during projectile impacts. Other proposed seam solutions are angled seams, reducing gap size, and cover plates. Continued modeling and experimental tests will down select for the best solution and improvement to seam design.